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Sand Waves That Impede Navigation of Coastal Inlet Navigation Channels

by Shelley Johnston Whitmeyer and Duncan FitzGerald

PURPOSE: Large bed forms, such as dunes or sand waves, can pose a navigation hazard for inlet channels (Pope 2000). Understanding the conditions causing their formation can be an aid in navigation channel management. This Coastal and Hydraulics Engineer Technical Note (CHETN) is concerned with large bed forms that chronically or periodically encroach on the authorized navigation depth. Smaller bed forms have been observed in many (perhaps most) other inlets, but because they do not hinder navigation, they are not discussed in this CHETN. Navigation channels with reported sand waves include the Columbia River, WA/OR; East Pass, Panama City, Fort Pierce, and St. Marys Entrance, FL; Merrimack River, MA, and Kennebec River, ME. This technical note discusses the characteristics of the bed forms found in those areas and conditions responsible for their development.

BACKGROUND: Large bed forms, as depicted in Figure 1, are called either sand waves or medium-to-large dunes. They have been documented to pose a navigation hazard if they extend about 1 m or higher above the channel floor (Ashley 1990; Boothroyd and Hubbard 1974). Although bed forms of various dimensions cover much of the seafloor, not all bed forms develop into sand waves. The development of sand waves depends on an ample supply of sand-sized material, strong current, and water depth great enough to accommodate these features. Bed form type is predicted based on grain size, flow velocity, and water depth parameters usually presented in a stability diagram, also called velocity-grain size plot or a velocity-depth plot (Figure 2) (Ashley 1990; Society of Economic Paleontologists and Mineralogists 1975; Southard 1971; Southard and Boguchwal 1990). Bed form size tends to increase with increasing velocity and grain size. However, if the grain size is too large or the current velocity is weak, there will be no significant bed form movement. If the current velocity is great, the bed form crest can be planed off, and the channel floor will be flat. Likewise, a lag deposit at the bed, which is a layer of denser or larger sized sediment left after finer material has been winnowed by a strong current, can inhibit bed form formation.

The nomenclature for bed forms can be confusing because there are multiple classification schemes. The term “bed form” encompasses all periodic depositional features in subaqueous environments that lie perpendicular to the dominant flow direction. Bed forms can be subdivided based on the size of the feature. Many classifications are similar, but slight differences can cause misinterpretation of published field observations. For example, three well-known classification schemes may be consulted by coastal engineers (Boothroyd and Hubbard 1975; Ashley 1990; and Dalrymple et al. 1978), as summarized in Tables 1, 2, and 3. The classifications of Boothroyd and Hubbard (1975) and Dalrymple et al. (1978) share common names, but the size categories differ. Ashley (1990) attempted a unified classification for bed forms, but it has not been commonly accepted because all bed forms are termed “dune,” which lacks the descriptive quality of the

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names employed in the other classifications. This CHETN follows the nomenclature of Boothroyd and Hubbard (1975).

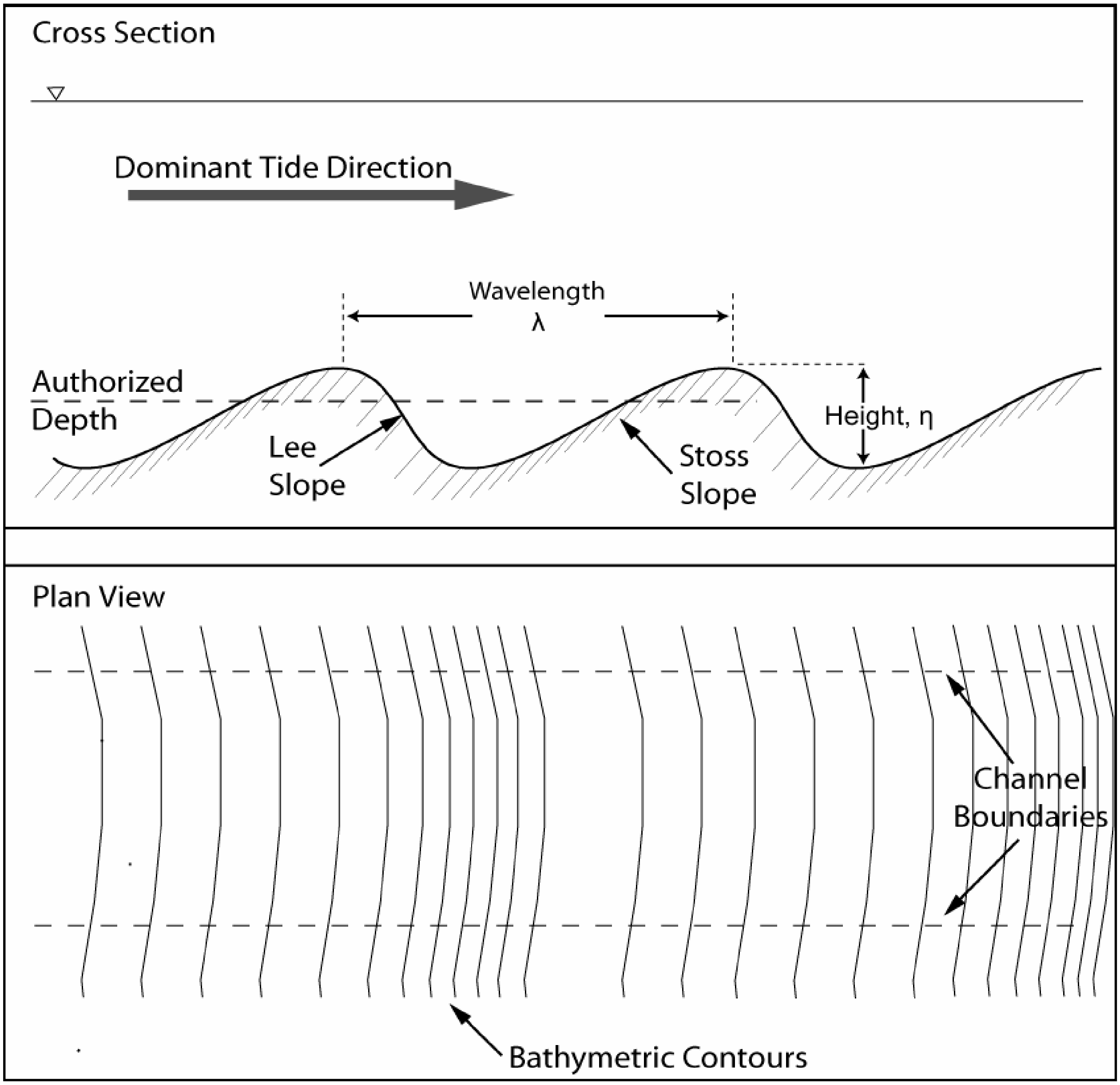

Figure 1. Definition of bed forms, as viewed along center-line axis of channel.

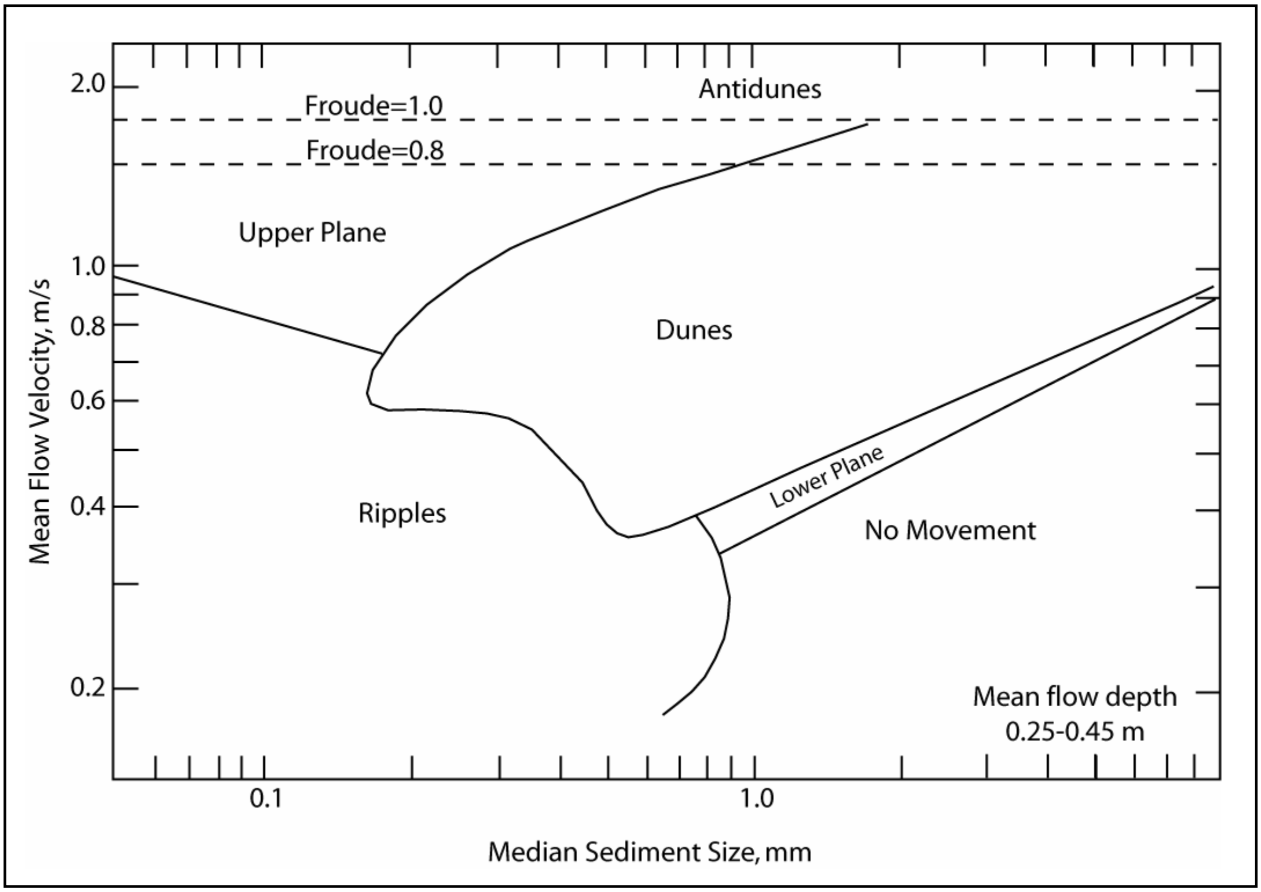

Figure 2. Velocity-grain size plot for predicting sea bed configuration (after Ashley 1990).

Table 1
Boothroyd and Hubbard (1975) Classification

Name	Wavelength	Description	Typical Flow Conditions
Ripples	< 0.6 m		Low
Megaripples	0.6 m - 6 m	• Sinuous to highly cuspate crests • Well-developed scour pits • Small height-to-wavelength ratio	High
Sand Waves	>6 m	• Straight to sinuous crests • Scour pits absent or poorly developed • Large height-to-wavelength ratio	Moderate

Table 2
Dalrymple et al. (1978) Classification

Bed form Type	Wavelength, m (λ)	Height, m (η)	Steepness	Morphological Characteristics
Small Scale				
Ripples	<0.3	<0.05	~10	Straight to linguoind in plan. Usually superimposed on larger forms as a late-stage modification.
Intermediate Scale				
Type 1 Megaripples	0.1 - 25.0 (6.1)	0.05 - 0.50 (0.18)	10 - 150 (44.6)	Straight to smoothly sinuous in plan, without small sinuous irregularities. Lack scour pits. Height remains constant along crestline. Flattened in section (λ/η usually>20). Wavelengths and heights poorly correlated (r=0.462 for N=255), with a best fit regression line of $\eta=0.0947(\lambda)^{0.346}$.
Type 2 Megaripples	0.05 - 14 (4.3)	0.05 - 0.70 (0.28)	6 - 34 (16.5)	Generally sinuous to lunate in plan, but may be straight with small sinuous irregularities. Scour pits well developed. Height variable along crestline. Profiles are steep (λ/η usually <20). Wavelengths and heights well correlated (r=0.788 for N=255), with a best fit regression line of $\eta=0.0865(\lambda)^{0.787}$. Lee faces are at the angle of repose, producing trough cross bedding.
Large Scale				
Megaripples Sandwaves	10.0 - 215.0 (40.6)	0.15 - 3.4 (1.86)	17 - 210 (44.1)	Straight to smoothly sinuous in plan. Scour pits absent. Height constant along crestline. Lee face inclination generally 10°-20°. Wavelength and heights moderately correlated (r=0.791 for N=58) with a best-fit regression line of $\eta=0.0635(\lambda)^{0.733}$. Megaripples (usually Type 2, but less commonly Type 1) are superimposed on the sandwaves.
Rippled Sandwaves	5.0 - 25.0 (12.9)	0.15 - 0.75 (0.38)	30 - 55 (36.6)	Morphologically similar to megarippled sandwaves but only have ripples or lower flow regime plane bed superimposed on their stoss sides.

Table 3
Ashley (1990) Dune Classification

First Order Descriptors				
Size:	**Small**	**Medium**	**Large**	**Very Large**
Spacing	0.6-5 m	5-10 m	10-100 m	>100 m
Height	0.075-0.4 m	0.4-0.75 m	0.75-5 m	>5 m
Shape:	2-Dimensional			
	3-Dimensional			
Second Order Descriptors (important)				
• Superposition: simple or compound. • Sediment Characteristics (size, sorting).				
Third Order Descriptors (useful)				
• Bed form profile (stoss and lee slope lengths and angles). • Fullbeddedness (fraction of bed covered by bed forms). • Flow structure (time-velocity characteristics). • Relative strengths of opposing flows.				
Dune behavior-migration history (vertical and horizontal).				

Flow Velocity. Flow conditions can be classified as subcritical or supercritical (alternatively, termed lower or upper flow regime). Subcritical flow occurs if Froude number $Fr < 1$, whereas supercritical flow occurs if $Fr > 1$. The Froude number is defined as the ratio between the flow velocity and the theoretical long-wave velocity:

$$Fr = \frac{U}{\sqrt{gh}} \tag{1}$$

where

U = mean flow velocity

g = acceleration of gravity

h = water depth

In a lower flow regime, increasing the flow velocity will increase the size of the bed forms present, assuming that the grain size remains constant (Simons and Richardson 1961). When flow is initiated over a sandy bed with sufficient sand supply, ripples are the first to develop, then megaripples with superimposed ripples, and then sand waves (Boothroyd 1978). Bed form size will increase as flow velocity increases until a Froude number of ~0.8 is reached. Bed forms between a Froude number of 0.8 and 1 will be washed out and will disappear. In an upper flow regime, the seabed will transition from a plane bed to standing waves and, then, finally to antidunes. Navigation channels discussed in this study experience subcritical flow, so only ripples, megaripples, and sand waves are present; antidunes are not observed in coastal inlets.

Flow Depth. Sand waves obstruct navigation only if they extend above the authorized channel depth. If the channel is deeper than the authorized depth or the bed form heights are low, their presence may be of no consequence to navigation. However, bed forms may be a problem even in deep-draft channels, such as St. Marys Entrance, where they form along the shallow side of the

channel and migrate into the channel from adjacent areas. The presence and significance of sand waves may also change seasonally with changing water level. In the Columbia River, sand waves may limit navigation depth in the fall and winter, when the river stage decreases.

Water depth does not seem to be a controlling factor in the development of bed forms unless the water is shallow relative to the height of the bed form. The literature is consistent that there is an upper limit for bed form height given a certain water depth. Considering the most extreme case of shallow water, the crest of a bed form will not extend above the water surface. However, in deep water, sand wave height is independent of water depth (Aliotta and Perillo 1987; Bokuniewicz et al. 1977; Dalrymple et al. 1978; Flemming 2003; Southard 1971; Southard and Boguchwal 1990). As the bed form builds vertically into the water column, the flow above the crest is constricted, and velocity will increase. At this point, the water depth begins to limit further growth of the bed form. A sand wave study in Long Island Sound found that bed form height was independent of the depth (h) until the height exceeded $0.086h^{1.19}$ (Bokuniewicz et al. 1977).

One of the few studies to document depth-limited bed forms was for the River Rhine in Germany (Carling et al. 2000). Here, changing river stage provided an opportunity to study the effect of decreasing water depth. It was observed that sand wave crests eroded as the river stage dropped. Carling et al. (2000) also noted that superimposed bed forms eroded as they migrated up the stoss side (the low angle up-current side of the bed form, see Figure 1) of the primary bed forms. As the superimposed megaripples approached the crest of the larger sand waves, the bed forms were not sand-supply limited, as the primary bed forms beneath the superimposed bed forms would provide sand. Therefore, their decrease in height was attributed to a decrease in depth, which alters the velocity profile and shear stresses.

In contrast to the River Rhine studies, there are numerous publications documenting weak or no relationship between water depth and bed form size. Studies from the Bay of Fundy, the Irish Sea, and the North Sea found no correlation between sand wave height and water depth (Armstrong et al. 1996; Bartholdy et al. 2002; Dalrymple et al. 1978; Dingle 1965; Jones et al. 1965; McCave 1971; Rubin and McCulloch 1980; Stride 1970). If the flow depth is greater than six times the sand wave height, the sand wave height is independent of the water depth (Rubin and McCulloch 1980). Therefore, it is possible that the sand waves in these studies had not developed to the point where they were depth limited, and they were instead limited by the amount of available sediment or the current velocity. It is difficult to differentiate the effect of grain size from that of current speed because the two parameters are related. Large grain sizes or lag deposits, which might develop in areas with strong currents, may limit bed form height because the sand sized material available to create the bed forms is reduced (McCave 1971). On the other hand, weak currents may lack the sediment transport potential to accrete large sand waves (Dingle 1965). Fine sand and/or strong currents may also decrease the height of sand waves because suspended sediment can be deposited in the trough of the sand wave, thereby decreasing the sand wave height (McCave 1971).

Grain Size. Grain size may also control the distribution and size of bed forms (Southard 1971; Southard and Boguchwal 1990; Zarillo 1982). If the sediment is too fine or too coarse, sand waves will not develop. In Long Island Sound, sand waves were absent in areas where sediments comprised more than 10 percent mud or more than 12 percent coarse sand (Bokuniewicz et al. 1977). In the Bay of Fundy, sand waves only developed in areas where the sediment grain size

exceeded 0.274 mm (Dalrymple 1984). In the Southern Bight of the North Sea, sand waves were observed in areas were the surface sediments were less than 0.5 mm and less than 15 percent mud (0.05 mm) (Terwindt 1971). In the Humboldt Entrance Channel, WA, bed forms appear to be confined to areas where the grain size is greater than 0.23 mm (Johnston et al. 2003).

In the North Sea, the northern boundary of McCave's (1971) sand wave field study separated areas where suspended or bed load dominated the transport regime. South of this boundary, the sand was coarse enough to remain as bed load and sand waves developed. North of the boundary, the sand was finer and suspended transport increased. McCave (1971) linked the absence of bed forms to an increase in suspended load.

In the Lillooet River, British Columbia, bed forms appeared "washed-out" despite the fact that the Froude number indicated subcritical flow (Fr < 1) (Prent and Hickin 2001). Prent and Hickin (2001) concluded that bed forms were diminishing in size because the finer sediment was suspended in the flow, and not because the bed configuration was approaching the upper regime plane bed.

In the Gradyb Channel, Danish Wadden Sea, grain size correlated well to the bed form size (Bartholdy et al. 2002). In this channel, bed forms were 1.3 to 3.6 m high, the water was about 10 m (mean low water springs) deep, and the mean sediment size decreased from 0.56 mm at the inner end of the channel to 0.33 mm at the seaward end. Sand wave height decreased from 3.7 to 0.8 m as grain size decreased along the length of the channel. This decrease in sand wave height was attributed to a change from bed load dominated transport in the inner channel to suspended transport in the outer channel where the sand was finer (cf, McCave 1971). Bed form height also decreased in the inner section of the channel where the sand was greater that 0.5 mm because this area was sand starved, not because of the change in grain size. The relationship observed with wavelength was more complicated because the wavelength increased if the sand became finer than 0.41 mm. In this situation, the wavelength increased as the bed form began to flatten and disappeared.

Sand waves in San Francisco Bay were found to decrease in height with diminishing grain size. Rubin and McCulloch (1980) attributed this phenomenon to the response time of the sand waves to reversing tidal flow. In tidal environments, the equilibrium geometry of bed forms fluctuates with changing flow conditions. When flow speed declines, the equilibrium bed form dimensions are reduced. Sand waves composed of fine-grained sand will decrease in size more quickly than those composed of coarse-grained sand because it is easier to move fine-grain sediment. Therefore, fine-grained sand waves respond to opposing tidal flow, which diminishes their size, more readily than coarse-grained bed forms, and they are generally smaller.

Other Factors. Two environmental factors may limit applicability of predictive formulas, unsteady current and availability of sediment. These are discussed next.

Unsteady current. Although laboratory experiments and theoretical analyses provide insight into the fundamental physical processes controlling the development and geometry of bed forms, they have limited relevance to natural systems because the response of the seabed to flow conditions is not instantaneous, and the availability of sand-sized material needs to be considered. As a result of these and other complicating factors, there is not a unique relationship between flow velocity

(shear stress) and bed form size. In order to relate the results of these experiments and analyses to tidal inlets, understanding is required of how the seabed state and flow conditions are coupled.

The lag-time or response time is defined as the time required for the bed form to adjust to a changing flow condition. It is determined by:

a Initial size of the bed form (Bokuniewicz et al. 1977).

b Rate of sediment transport (Allen 1976; Bokuniewicz et al. 1977).

c Magnitude and rate of change in flow conditions (Allen 1976).

Bokuniewicz et al. (1977) derived the following equation to describe the response times of bed forms observed in Long Island Sound:

$$t = \frac{\eta\delta\lambda}{j\left(2\lambda+\delta\right)} \tag{2}$$

where

t = response time

δ = distance moved by the bed form

$\bar{j}$ = sediment transport rate

λ = bed form wavelength

η = bed form height

The example calculation presented by Bokuniewicz et al. (1977) assumes that $\bar{j}$ is 0.01 cu cm/cm/sec, $2\lambda/\eta = 20$, and δ is 0.2λ. These values are representative of the conditions in Long Island Sound. The results of this exercise provided estimates of response times for bed forms in Long Island Sound based on sand wave height. It would take about 6 months before a 4-m-high sand wave reversed asymmetry. In a tidal inlet, the sediment transport rate would be greater, and the bed forms would be smaller. Therefore, the response time would be shorter, and bed forms may change asymmetry within a single tidal cycle or show morphologic changes during a neap-spring tidal cycle.

Terwindt and Brouwer (1986) studied the lag time in the Westerschelde Estuary along the southwestern coast of the Netherlands. Westerschelde Estuary is a flood-dominated estuary and the peak spring flood tides are ~0.8 m/sec whereas the peak neap flood tides are only ~0.4 m/sec. There is a periodic monthly cycle during which bed form height increases during the spring tide. Bed form height increases as the current accelerates; however, the maximum bed form height lagged behind the peak current velocities by one to three tides. The correlation between wavelength and peak flood current is less significant.

Allen (1976) presented a conceptual model of how a bed form field will respond to changes in the flow regime. In this model, he assumed that the mean dimensions of a bed form field adjust to a

new flow regime through the creation/destruction of bed forms. As new bed forms are created, they immediately take the dimensions in equilibrium with the flow conditions present at the time they were created, and these dimensions remain constant throughout the bed form's existence. Eventually, the older dunes decompose, and the mean dimensions of the bed form field equilibrate with the hydrodynamics.

Given the variability in response time, it is likely that some environments are never at equilibrium with the flow conditions. This is especially true in a tidal inlet channels that continuously changes. The exact duration of the response time is site specific.

Sand availability. The thickness of the surficial sediment layer may limit the development of bed forms, because sediment supply needed to construct the bed form will be limited. For example, in the Bahia Blanca Estuary (Argentina), the sand wave field terminated where the surficial sand sheet became too thin (Aliotta and Perillo 1987). Along the northern boundary of the bed form field, the water depth and grain size were similar on either side of the boundary, but the thickness of the unconsolidated surficial sand decreased. This variation in sediment thickness controlled the location of the boundary.

A second example is the Teignmouth Estuary, where the size of small ripples on Spratt Sand, an intertidal shoal, was found to vary with the availability of sand. The shoal is covered with a veneer of sand 0.1 to 0.3 m thick. If this sand sheet is eroded, the height of the ripples decreases from ~0.2 m to less than 0.1 m (Hoekstra et al. 2004; van Lancker et al. 2004).

The third example of a sand-limited bed form field comes from the North Sea, where an expansive sand wave field terminated when the sediment supply diminished (McCave 1971). Bed forms were absent in the deep channels where strong currents had removed the sand fraction, leaving a gravel lag. The currents had removed the finer sand and left behind a gravel lag deposit, which prevented sand waves from growing.

SUMMARY OF SITES WITH IMPEDING BED FORMS: This study focuses on seven federally maintained navigation channels where sand waves have obstructed navigation. These sites include the Columbia River, WA/OR; East Pass, Panama City, Fort Pierce, and St. Marys Entrance, FL; the Merrimack River Entrance, MA; and the Kennebec River, ME (Figure 3; Table 4). All of these sites have some tidal influence.

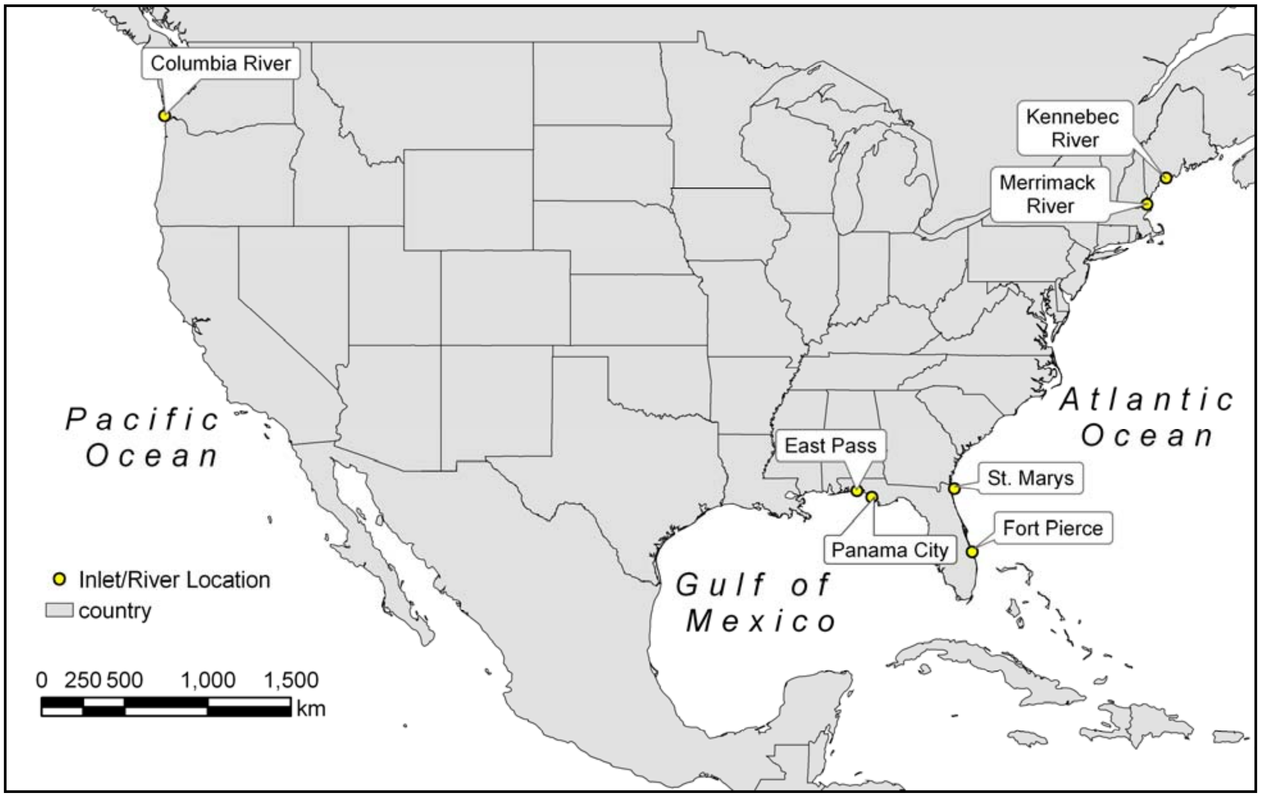

Figure 3. Location map for Federal inlet navigation channels reported to have bed forms that impede navigation.

Table 4
Inlet and Navigation-Impeding Bed Form Characteristics

Location	Depth, m	Current Velocity, m/sec	Grain Size, mm	Tide Range, m	Wave Height, m	Bed Form Height, m	Bed Form Length, m
Columbia River	12.2 (CRD)[1]	0.6[2]	0.35[1]	~0.76[2]	0.46[2]	4.6[1]	305[1] 92[1]
East Pass	3.7 (mlw)	1.3 (ebb) 0.9 (flood)	0.25-0.5	0.41[3]	1[4]	0.5-1.5	30-50
Panama City	9.8 (mlw)	0.75 (ebb)[1] 0.7 (flood)	0.2-0.35	0.41[3]	1[4]	2-5[5]	30-60[5]
Ft. Pierce	9.8 (mlw)[6]	1.4 (ebb)[7]	0.39	0.9[7]	1.1	8 <1	400 80
St. Marys	15.5 (mlw)	1.5 (ebb)[8]	0.32[9]	2.0[3]	1.1[10]	4	750
Merrimack River	3.66 (mlw)		1	2.74[3]	1.0[11]	2[12]	20-30[12] 70-100[12]
Kennebec River	8.2 (mllw)[13]	1.19 (ebb) 0.82 (flood)	0.45	2.93[3]	0.9[14]	10 6.5 0.2-0.6	400-1,200 50 2-3

Sources:
1 Levin et al. 1992. CRD is Columbia River Datum.
2 Granat and Alexander 1991.
3 NOAA Center for Operational Oceanographic Products and Services, http://tidesandcurrents.noaa.gov/index.html.
4 National Data Buoy Center, sta 42039, http://www.ndbc.noaa.gov/station_history.php?station=42039, mean wave height from 1995-2004.
5 Lillycrop et al. 1989.
6 Personal communication, Mr. Rick McMillen, U.S. Army Engineer District, Jacksonville (21 Oct. 2005)
7 Walton 1974.
8 Aubrey et al. 1991.
9 USACE, Coastal Inlets Research Program, http://cirp.wes.army.mil/cirp/cirp.html. Retrieved November 2005.
10 Wave Information Study (2005). "U.S. Army Corps of Engineers Wave Hindcast Data," http://frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html Retrieved 17 January 2006.
11 National Data Buoy Center, sta 44029, http://www.ndbc.noaa.gov/station_history.php?station=44029, mean wave height from 2004.
12 FitzGerald et al. 2002.
13 Personal communication, Mr. Edward O'Donnell, U.S. Army Engineer District, New England (18 October 2005).
14 National Data Buoy Center, sta 44031, http://www.ndbc.noaa.gov/station_history.php?station=44031, mean wave height from 2004.

Columbia River. Sand waves are a navigation problem in the Columbia River (Granat and Alexander 1991; Levin et al. 1992). Near Portland (river mile 100), the sand waves are 100 m long and 3 m high (Levin et al. 1992). In this area, the authorized depth is 12.2 m (CRD). During the summer, as the river stage decreases, the crests of these bed forms often encroach on the authorized channel depth. Between February and March 1986, monthly surveys showed 30 m of sand wave migration (Levin et al. 1992). However, there was no movement the following month due to changes in flow conditions. During the Granat and Alexander (1991) study, the peak current velocities recorded on 5-6 October 1988 were 0.6 m/sec, and the tide range was about 0.46 m (Granat and Alexander 1991).

East Pass. East Pass, which is located along Florida's northern Gulf coast (30˚23'N and 86˚31'W), allows passage from the Gulf of Mexico into Choctawhatchee Bay. The first Federal project for East Pass began in 1930, when the inlet was dredged to a depth of 1.8 m (mlw). The channel was deepened to 3.7 m (mlw) in 1940 to accommodate the needs of the Eglin Field Military Reservation. In an effort to alleviate channel shoaling, jetties were built in 1969. Since 1969, the mouth of the inlet has been stabilized by the jetties, but the throat has continued to

migrate east as evidence from persistent erosion along the eastern side of the channel (Morang 1992).

The thalweg and channel banks of East Pass are covered with bed forms ranging from 30-50 m in length and 0.5 – 1.0 m in height (Figures 4 and 5).

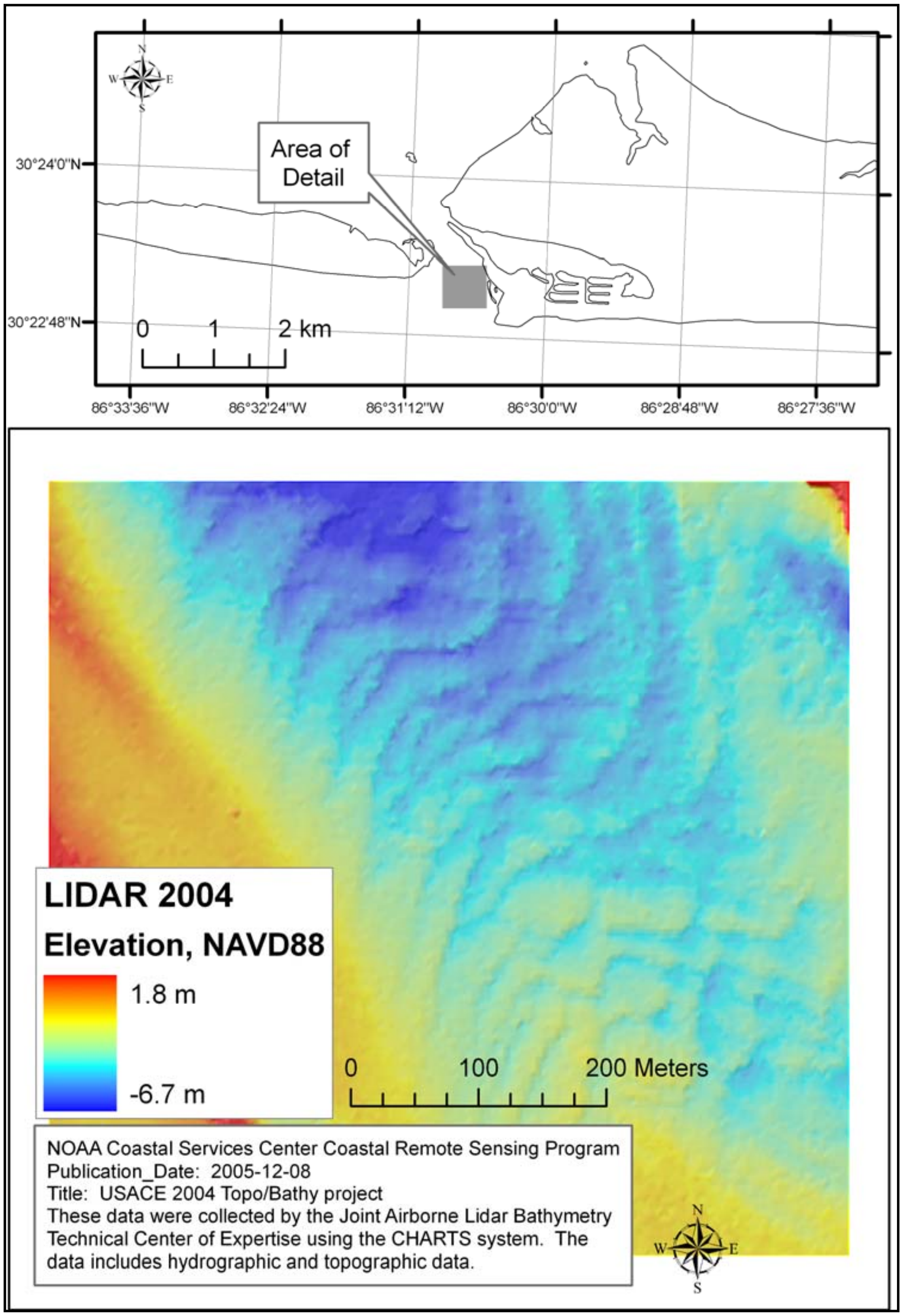

Figure 4. Bathymetric survey of East Pass showing sand waves in channel.

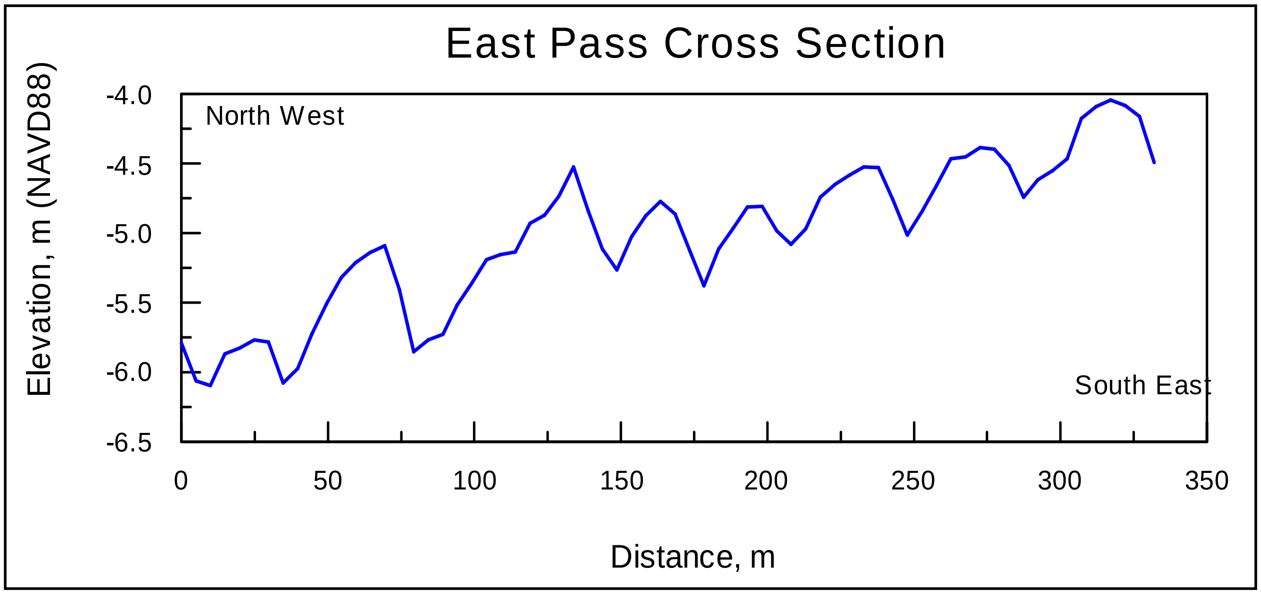

Figure 5. Cross section of sand waves in East Pass, FL, Entrance Channel

Panama City. Panama City Inlet was artificially created in 1934 and stabilized with dual jetties. One of the shoaling problems in this channel is caused by the development of sand waves with crests encroaching on the authorized channel depth (9.8 m mean low water (mlw)). Sand waves cover the floor of the inlet perpendicular to the center line from St. Andrew Bay toward the Gulf of Mexico. These features generally increase in size from the bay to the Gulf. The average height is 1.4 to 1.8 m, and the largest sand waves are up to 4.6 m (Lillycrop et al. 1989). Sand waves between the jetties are the most problematic to navigation and have to be dredged every 1-2 years (Levin et al. 1992). After dredging, the sand waves quickly redevelop. Within 4 months, heights of 1.8 to 2.4 m are typically observed, and within 18 months the sand wave heights reached their maximum pre-dredge height (Lillycrop et al. 1989). To mitigate this situation, the channel is over-depth dredged by 2.4 m, the average sand wave height, to reduce the frequency of dredging. The eastern side of the channel is relatively shallow and contains prominent bed forms. The thalwag abuts the west jetty and currents have scoured the channel to a depth of 15 m mlw (Levin et al. 1992). Presumably, strong currents have removed much of the unconsolidated sand-sized material and left a lag deposit along the west side of the entrance. Without an ample sand supply, sand waves are unable to develop.

Lillycrop et al. (1989) investigated the possibility of reducing the shoaling problem caused by the sand waves along the shallow east side of the channel by manipulating the current speed and sediment supply to the area. By reducing the current velocity, smaller bed forms would replace the larger ones. Alternatively, increasing the velocity would tend to eliminate the bed forms by transforming the system from lower to upper flow regime where bed forms are no longer stable. The proposed alternatives were numerically assessed and found to be impractical. To increase the flow to an upper flow regime, the current velocities would need to exceed 0.85 to 1.20 m/sec. To achieve these flow conditions, it was calculated that the jetties would have to be moved closer together to reduce the channel width and increase the current velocity. To reduce the sand wave height by decreasing the current velocity, the flow would have to decrease by 0.20 to 0.55 m/sec. To achieve this range of current velocity, the inlet width would have to be expanded to 953 m and

the channel be dredged to 16.8 m (mlw). Even then, the currents were predicted to decrease to only 0.27 m/sec. Any movement of the jetties would be costly; therefore, these alternatives were deemed impractical.

Fort Pierce. In 1921, Fort Pierce was created by the Fort Pierce Inlet District to provide local commerce with a port. Responsibility for maintenance of this inlet was transferred to the Federal government in 1935 (Walton 1974). Two rock jetties were built 183 m apart to stabilize the inlet. These have lengths of 549 m (north) and 366 m (south) (Rodriguez and Dean 2005).

This inlet has a mixed semidiurnal tide with a spring tide range of 0.9 m and a mean tide range of 0.8 m (Walton 1974). The peak ebb current is 1.4 m/sec (Walton 1974). Net longshore transport estimates range from 40,000 to 255,000 cu m/year (Table 5). There are several large sand waves in the Fort Pierce Entrance Channel (Figure 6 and 7). The largest of these features are 8 m high and 400 m long.

Table 5
Estimates of Longshore Transport for Fort Pierce Entrance

Source	Net Littoral Drift
U.S. Army Corps of Engineers (1963) Bruun (1966)	153,000-191,000 cu m/year South
Walton (1973)	40,000 cu m/year South 255,000 cu m/year South 215,000 cu m/year North

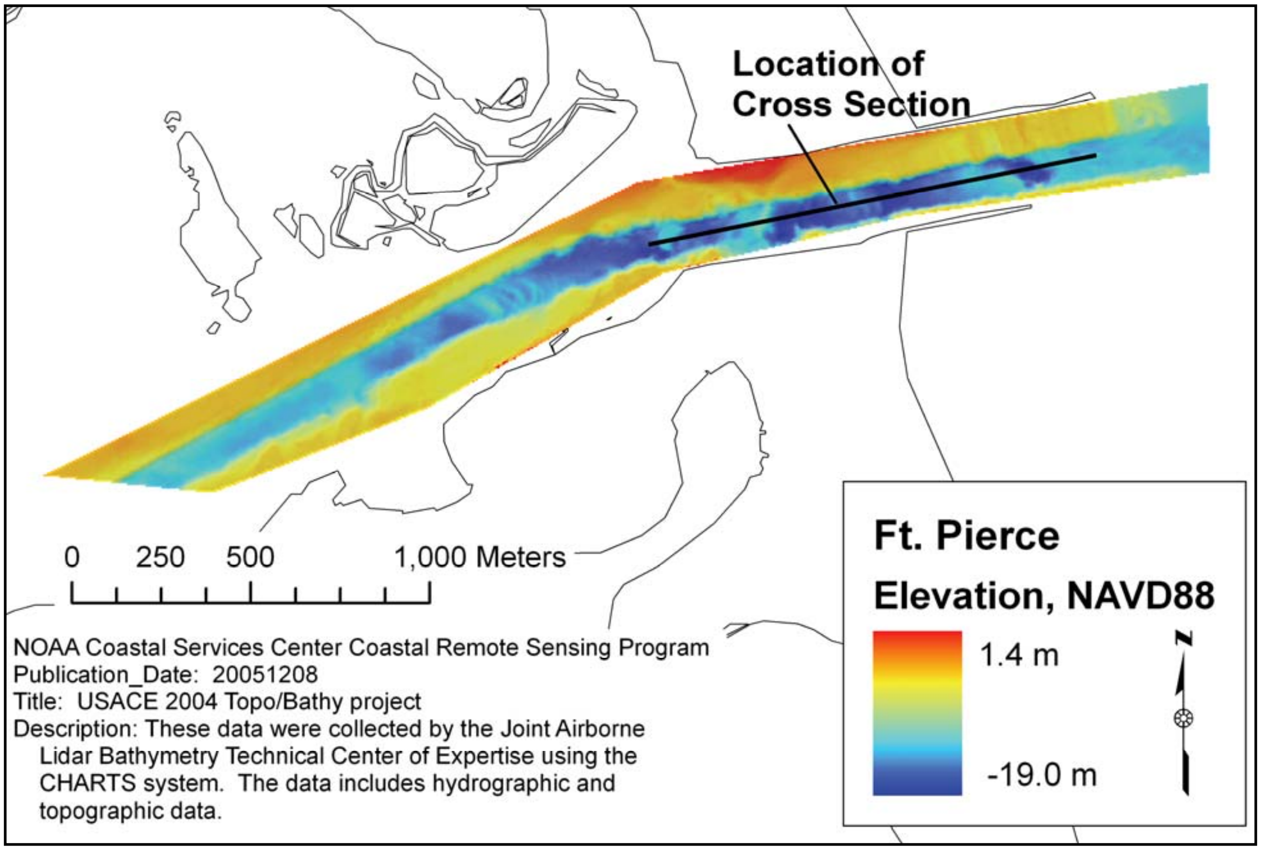

Figure 6. Bathymetric map of Fort Pierce, FL, Entrance Channel.

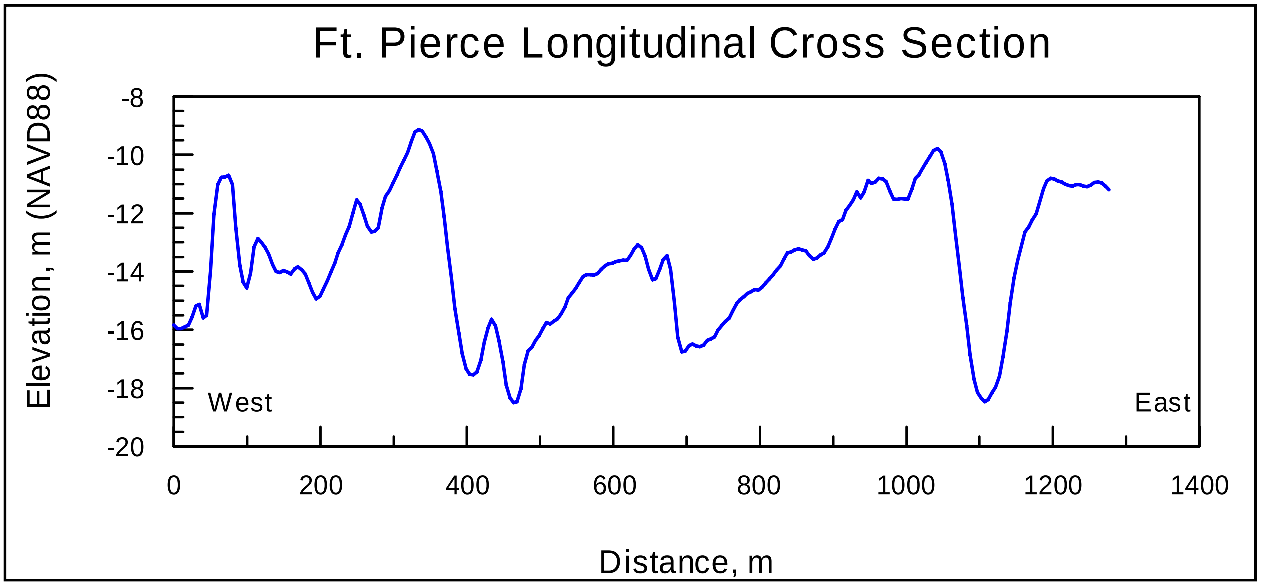

Figure 7. Cross section of bed forms in Fort Pierce, FL, Entrance Channel.

St. Marys Entrance. St. Marys Entrance Channel is a deep-draft navigation channel (15.5 m mlw) that connects Cumberland Estuary to the Atlantic Ocean. This channel provides access to the Kings Bay Naval Base to accommodate Trident submarines. The entrance was recognized as a

navigation channel as early as 1770 (Raichle et al. 1997). Jetties were constructed on either side of the inlet in 1896.

Sand is plentiful in this area. The two main sediment supplies are longshore transport on the adjacent beaches and the Cumberland Estuary. The net littoral transport in this area has been estimated between 69,000 to 459,000 cu m/year to the south (Table 6) (Dean 1988; Richards and Clausner 1988). However, the deep inlet channel most likely captures the gross transport (sediment moving from both directions), which is estimated to be between 399,000 cu m/year and 1,200,000 cu m/year (Knowles and Gorman 1991; Richards and Clausner 1988). The mean grain size in the inlet is 0.32 mm.

The entrance channel is ebb-dominant. The mean tidal range is 1.7 m, and the spring range is 2.0 m. The peak tidal current velocity is 1.5 m/sec (Aubrey et al. 1991). The largest bed forms in St. Marys Entrance are more than 4 m high and 750 m long (Figures 8 and 9). These features are located north of the navigation channel between the channel and the north jetty. The southern ends of these bed forms migrate into the navigation channel (Johnston et al. 2002).

Table 6
Estimates of Longshore Transport for St. Marys Entrance

Source	Littoral Drift, cu m/year	
Knowles and Gorman (1991)	1,200,000	Gross (value reported in abstract)
	900,000	Gross (value reported in conclusions)
	300,000	Net
Compiled by Richards and Clausner (1988)	382,000	Net (Dredging Records)
	535,000	Gross (Dredging Records)
	182,000	Net
	399,000	Gross
	69,000	Net (WIS)
	771,000	Gross (WIS)
Dean (1988)	459,000	Net

NOTE: All values have been rounded to the nearest 1,000 cu m.

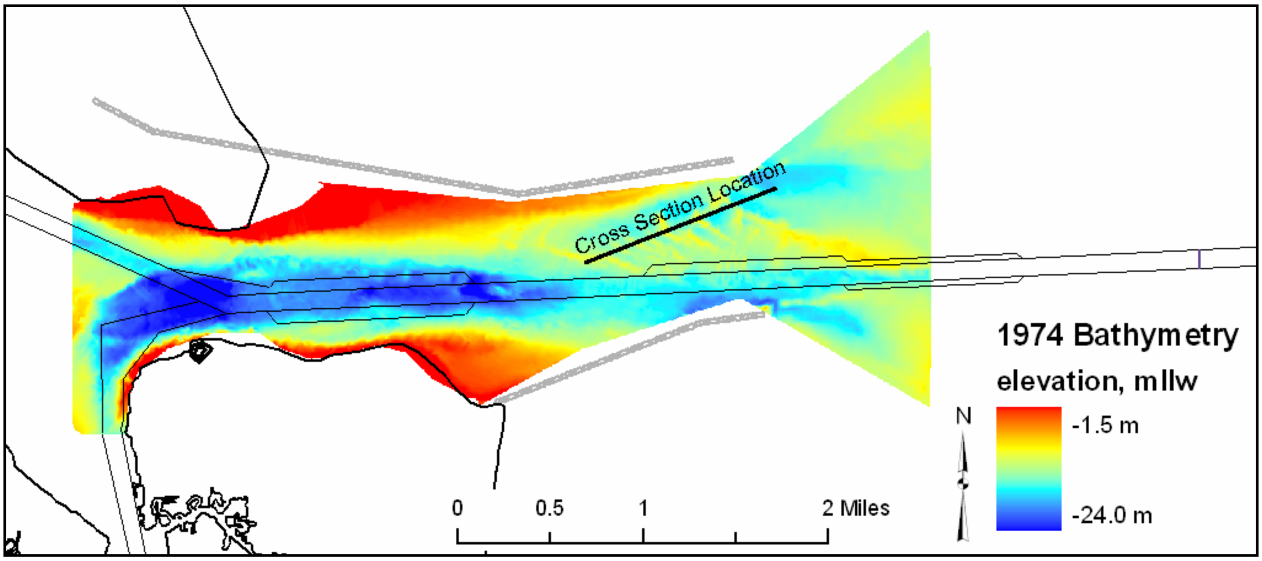

Figure 8. Bathymetric map of St. Marys Entrance, FL.

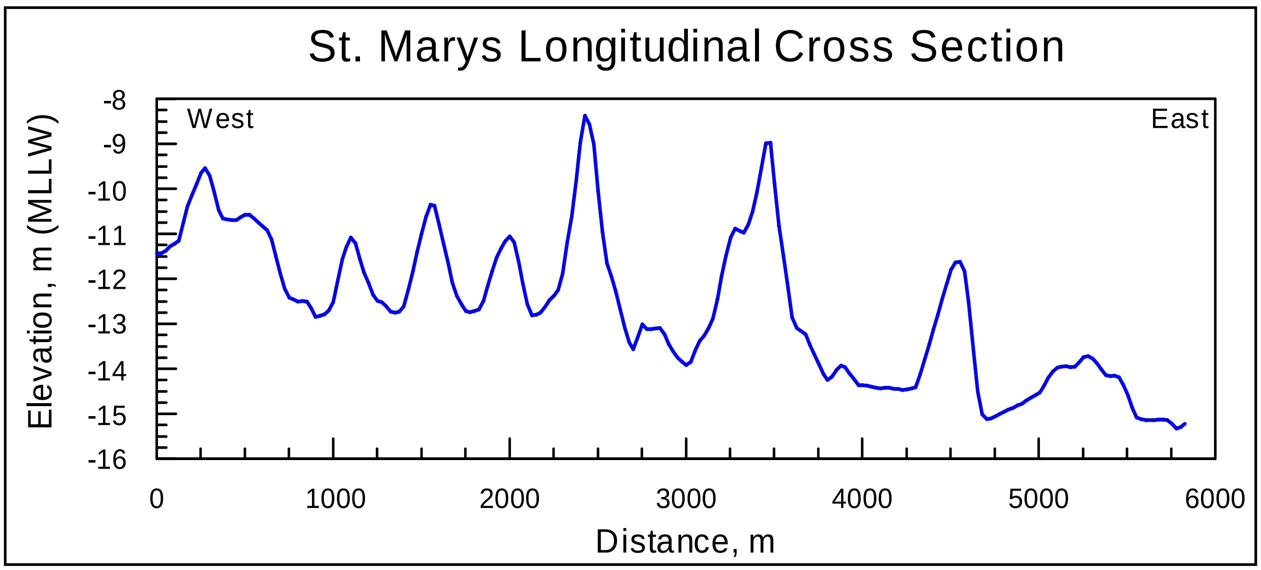

Figure 9. Cross section of sand waves at St. Marys Entrance, FL.

Merrimack River. The Merrimack River enters the Gulf of Maine in northern Massachusetts. The inlet is bounded to the north and south by barrier islands. The river and offshore fluvial marine deposits have supplied sand for barrier construction (Boothroyd and FitzGerald 1989). A Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) dataset of the region shows several ebb-orientated sand waves just seaward of the jetties and some smaller flood and ebb-orientated bed forms inside the jetties. The smaller ebb-orientated sand waves are 20 to 30 m long and the larger ones are up to 2 m high and 70 to 100 m long. The bidirectional bed form orientations inside the jetties delineate two mutually evasive sand transport pathways (FitzGerald et al. 2002). Flood-orientated megaripples occur along the southern shallow portion of the channel whereas ebb-orientated sand waves are found along the northern bank. The ebb-orientated sand

waves continue out seaward of the jetty across the ebb shoal, where they are deflected to the south by southwesterly currents generated by northeast storm waves.

Kennebec River. The Kennebec River Estuary is a bedrock cut valley located along the central peninsula coast of Maine. The morphology of this partially-mixed to stratified mesotidal estuary is controlled by glacially carved bedrock (Fenster and FitzGerald 1996). The primary sediment source for the lower Kennebec River is sand coming down the upper river through Merrymeeting Bay. The bay collects coarse-grained sediment from unconsolidated ice-contact and periglacial deposits (Fenster and FitzGerald 1996). During strong flows, this sediment is flushed out of the bay and into the estuary. The Kennebec River experiences semidiurnal tides with a mean tidal range of 2.6 m and spring tidal range of 3.5 m. The tidal prism is 16 times greater than the average fresh-water discharge (FitzGerald et al. 1989). Only during large spring freshets is the flood tide blocked by the seaward flowing freshet.

The authorized depth of the Kennebec River is 8.2 m mean lower low water (mllw), but navigation is often compromised by large sand waves. The largest transverse bars are 10 m high and 400-1,200 m long (Figures 10 and 11) (Fenster and FitzGerald 1996). Smaller bed forms (sand waves height = 6.5 m and wavelength = 5 0 m; megaripples height = 0.2-0.6 m and wavelength = 2-3 m) also develop, superimposed on the larger features, within the channel (Figure 11). The orientation of the sand waves was found to change seasonally. In the spring and early summer, the bed forms were ebb-orientated, whereas from late summer to early winter they were flood-orientated (Fenster and FitzGerald 1996). Fenster and FitzGerald (1996) concluded that seasonal changes in freshwater discharge were responsible for this change. They also noted that a survey completed just 1 day after dredging showed that the bed forms had reestablished. Although no migration was documented during this study, it is believed that these bed forms do migrate.

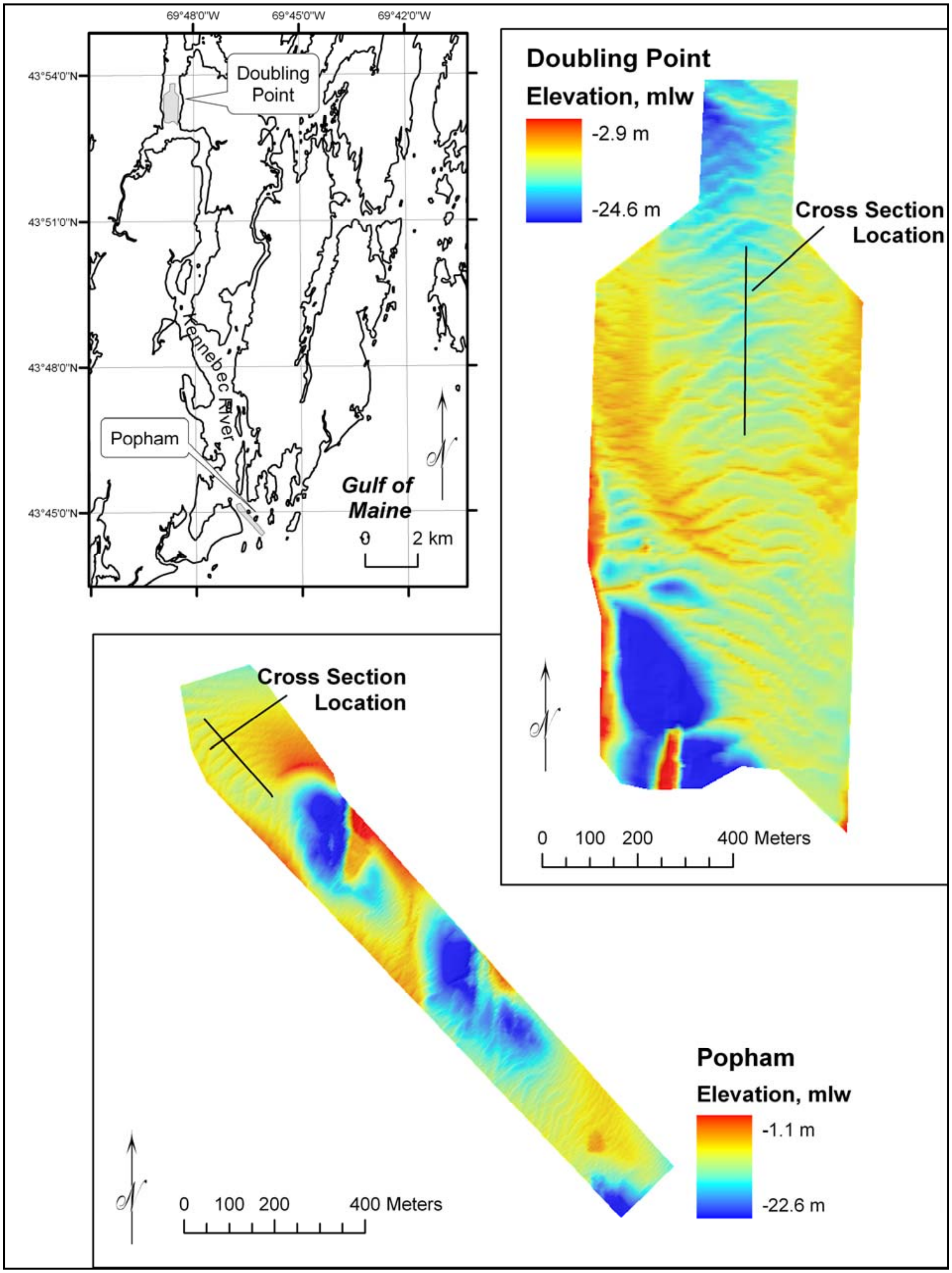

Figure 10. Bathymetric map of Kennebec River, ME.

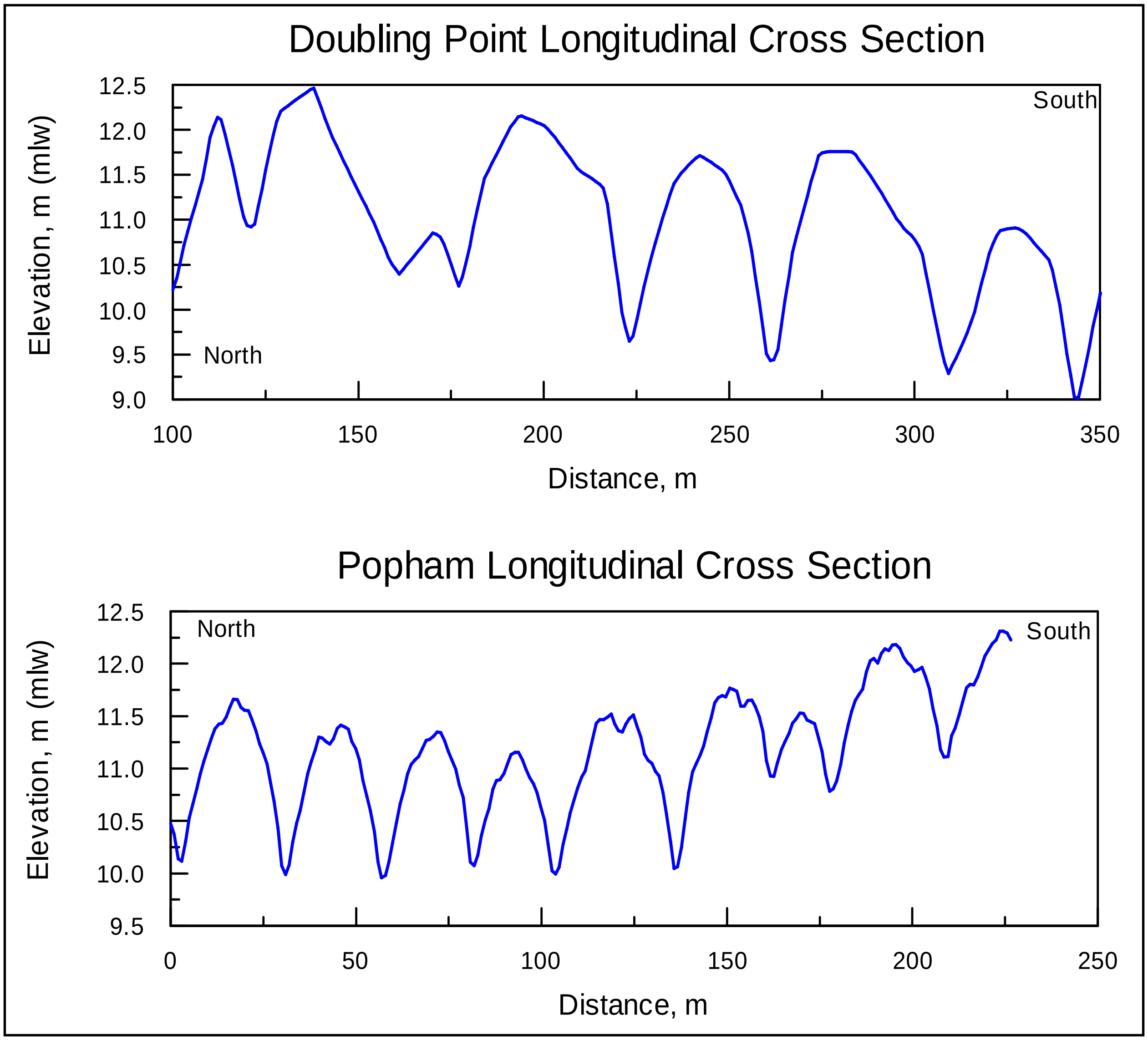

Figure 11. Cross section of sand waves at Kennebec River, ME. These surveys do not correspond in time or location with sand waves described by Fenster and FitzGerald (1996).

SUMMARY OF FINDINGS

Prediction of Seabed Configuration. The purpose of this study was to identify the sedimentologic and hydraulic conditions that promote development of sand waves in tidal navigation channels. Ideally, predictive capability is desired to estimate whether sand waves are likely to be present in a channel, to estimate their height and length dimensions, and what could be done to eliminate their hazard to navigation. This capability would be useful in engineering and management applications and is facilitated by understanding the physical processes that generate bed forms. Seabed stability plots are a useful tool for predicting the development of bed forms. Many variations of these plots have been published (e.g., Ashley 1990; Boguchwal and Southard 1990; Boothroyd and Hubbard 1974; Rubin and McCulloch 1980). Differences among plots can be attributed to the specific data set used to create the plot. For this CHETN, data sets from tidal

navigation channels are compared to the existing stability diagrams to evaluate if the development of sand waves can be accurately predicted.

The data analyzed were compiled from various sources. The database contains 132 Federal navigation channels. Data collected includes peak flood and ebb current velocities, mean grain size, average and spring tidal range, average and significant wave height, and entrance width and depth. Depending on the inlet in question, the fields were populated with varying degrees of success. The number of inlets included in each of the following analyses depends on the completeness of the database.

This study identifies sand waves in navigation channels over a large range of water depths from 3.7 m to 15 m. Inlets with sand waves have a median grain size between 0.2 and 1 mm, and the grain sizes of all the inlets range from 0.16 to 1 mm. Large bed forms are not observed in areas with a grain size smaller than 0.2 mm. The peak velocity of the inlets surveyed in this study ranged from 0.4 to 2.7 m/sec, and the subset containing bed forms ranged from 0.6 to 2.4 m/sec.

Hayes (1979) proposed an inlet classification to describe the energy regime at an inlet based on tide range and wave height. Application of this classification scheme has proven fruitful in explaining morphological differences among inlets. Here, the classification was applied to assess if inlets with and without sand waves fell into different energy regimes (Figure 12). As seen in Figure 12, there is no separation between inlets with and without bed forms, making the Hayes (1979) a poor indicator of bed form development.

Neither the stability diagrams nor the energy regime accurately predict the distribution of sand waves in tidal navigation channels. Water depth, flow velocity, and grain size of channels without sand waves are not distinctly different than channels with bed forms. Figures 12 and 13 show that the two subgroups of channels are not segregated by grain size, flow velocity, wave height, or tidal range. This lack of predictive power suggests that additional factors determine the development of sand waves. The availability of unconsolidated sand-sized sediment is likely a primary control on the development of sand waves. Even under ideal flow conditions, it is not possible to build large bed forms, if sand is not available. Also, the amount of sand may be made unavailable due to the development of a lag deposit on the channel floor.

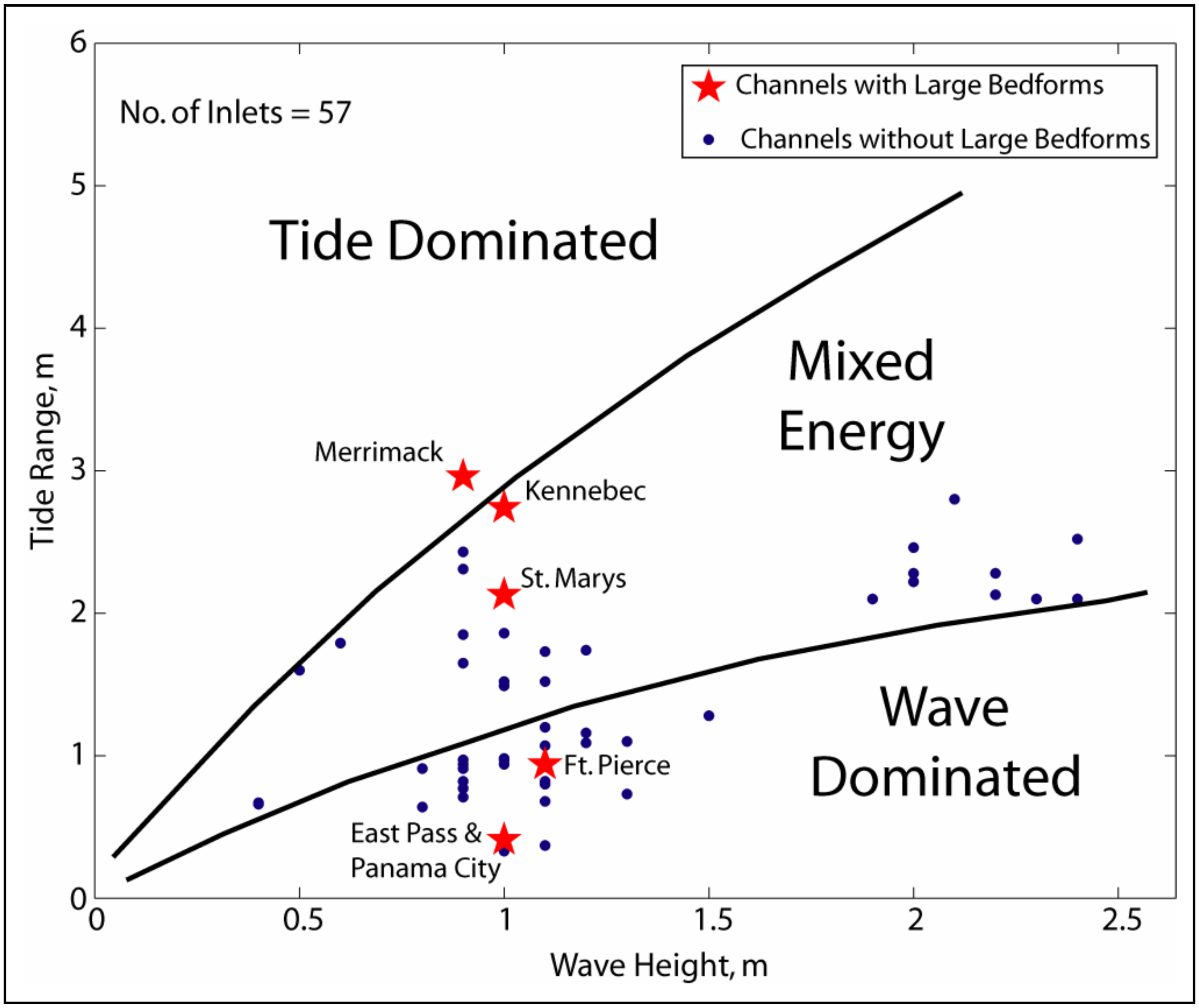

Figure 12. Inlets with and without bed forms plotted according to Hayes (1979) tide and wave energy classification.

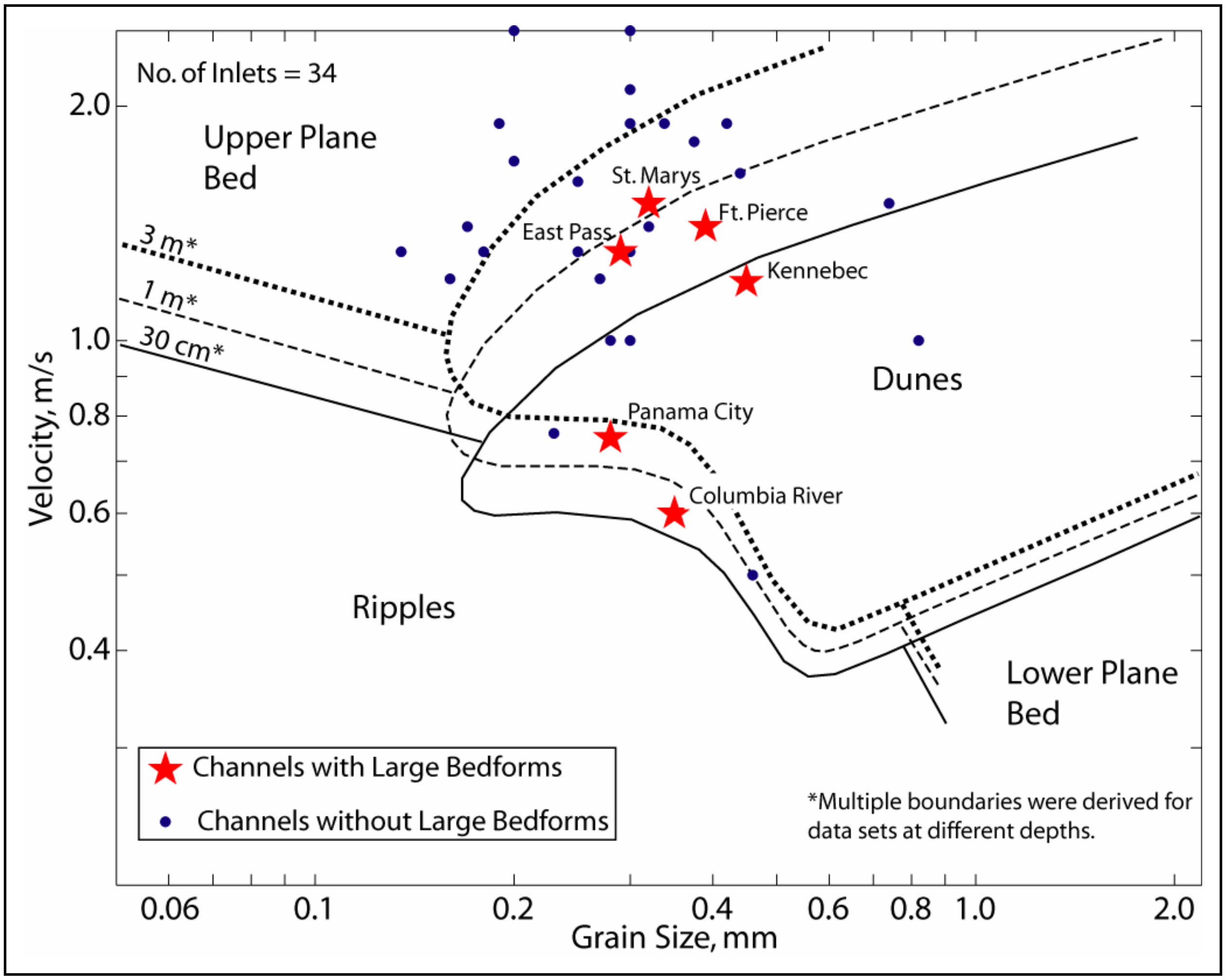

Figure 13. Bed form stability after Southard and Boguchwal (1990).

Prediction of bed form dimensions. Prediction of bed form size (height η and length λ) is of central interest because of wide-reaching applications. For example, if a new inlet is to be opened or an existing channel is to be deepened, the potential of large bed forms to form can be accessed. There are physical factors governing these relationships; however, the success of their application is varied. The existence of numerous formulas indicates that the models are site-specific or that additional factors control bed form stability and are not accounted for in the existing formulas (Table 7). Conceptually, the height of the bed form may be limited by water depth because flow constriction over the crest may accelerate and erode the crest. The physical reasoning for the wavelength and depth relation is that the spacing of large-scale bed forms is controlled by the scale of turbulent eddies in the water which, in turn, is correlated to water depth.

Observations from channels with large sand waves were analyzed here to assess the success of these models in navigation channels. The results indicate wavelength and bed form height are generally underpredicted (Figures 14 and 15). Also, it is seen that there is little systematic variation with depth for either bed form height or wavelength. This lack of predictive capability reinforces a previous conclusion that flow depth has little control on bed form height or wavelength except in shallow water where bed forms are depth-limited. Predictors based on grain

size and flow velocity have not been evaluated because, to the authors' knowledge, no equations relating bed form size to flow velocity exist, and only ripple dimensions are known to be related to grain size. The Yalin (1964) and van Rijn (1984) equations do incorporate shear stress, which is closely related to flow velocity. These equations could not be evaluated due to a lack of data.

Table 7
Predictive Bed Form Equations

Formula	Reference
Height Prediction	
$\eta = \frac{h}{6}\left(1 - \frac{\tau_{cr}}{\tau_{os}}\right)$ *for* $\tau_{cr} \leq \tau_{os} \leq 17.6\tau_{cr}$ Within this range of shear-stress the equation can be simplified to $\eta < 0.167h$ or for depth-limited bed forms $\eta = 0.167h$.	Yalin (1964) Soulsby (1997) The simplified equation is evaluated here because the authors had no data on shear-stress for the seven navigation channels in question.
$\eta = 0.086h^{1.19}$	Allen (1970)
$\eta = 0.285h$	
$\eta = 0.11h\left(\frac{d_{50}}{h}\right)^{0.3}\left(1 - e^{-0.5T_s}\right)\left(25 - T_s\right)$ *for* $\tau_{cr} \leq \tau_{os} < 26\tau_{cr}$	van Rijn(1984) Soulsby (1997) This equation was not evaluated because of lack of available data for the seven navigation channels in question.
$\eta = (0.36h) - 0.026$	Gabel (1993)
$\eta = (0.247h) + 0.0156$	Mohrig and Smith (1996)
$\eta = (0.215h) + 0.0163$	Prent and Hickin (2001) Site A[1]
$\eta = (0.178h) + 0.091$	Prent and Hickin (2001) Site B[1]
Wavelength Prediction	
$\lambda = 5h$	Yalin (1964)
$\lambda = 2\pi h$	Yalin (1977) Soulsby (1997)
$\lambda = 1.16h^{1.55}$	Allen (1970)
$\lambda = 7.3h$	van Rijn (1984) Soulsby (1997)
$\lambda = (6.42h) - 0.27$	Gabel (1993)
d_{50} = median grain size λ = wavelength η = bed form height h = water depth τ_{cr} = threshold bed shear-stress for sediment motion τ_{Os} = bed shear-stress due to friction $T_s = \frac{\tau_{Os} - \tau_{cr}}{\tau_{cr}}$	
[1] Prent and Hickin (2001) developed two relationships between bed form height and flow depth based on their two sites, A and B. Site B typically had stronger current flows and coarser sediment than Site A.	

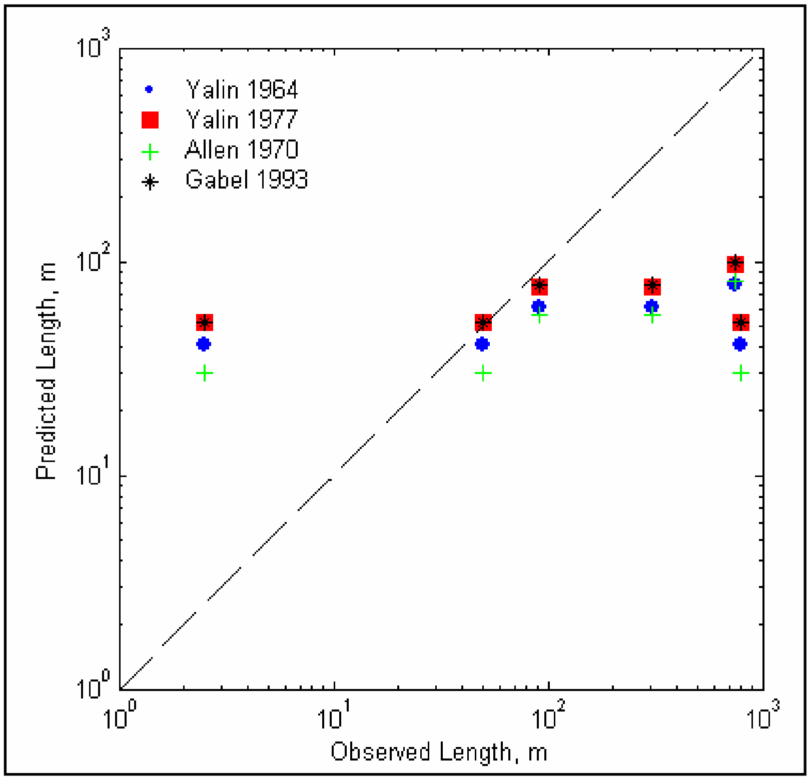

Figure 14. Observed vs. predicted bed form wavelength.

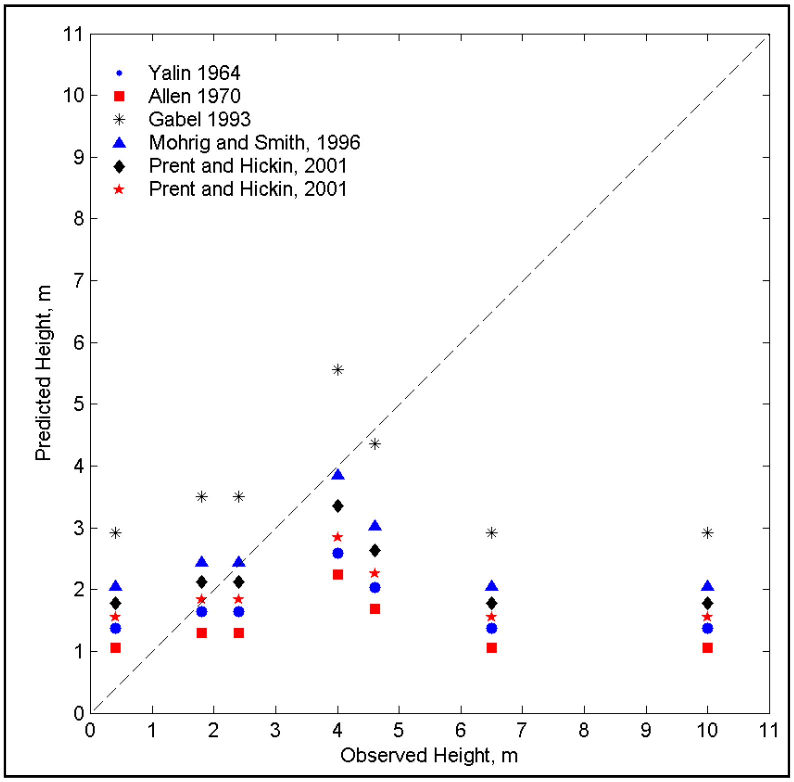

Figure 15. Observed vs. predicted bed form height.

GUIDANCE FOR MITIGATING LARGE BED FORMS: There are three approaches for minimizing navigation hazards related to bed forms in channels, (1) alter the hydraulic and/or sediment conditions to hinder the development of bed forms, (2) reduce bed form size by dredging, or (3) intercept sand waves before arrival to the channel. All approaches need to be evaluated on a site-specific basis.

Ideally, decreasing the current velocity to less than 0.6 m/sec would reduce the size of the sand waves. To accomplish this, the cross-sectional area of the inlet would have to be increased either by deepening the channel or making it wider. Potential negative side effects of this action are significant. For example, a larger inlet cross section would promote deposition in the channel, increasing maintenance dredging requirements and causing inlet instability (tendency for closure). Increased deposition in the channel would remove sand from the littoral system and contribute to erosion of the adjacent shoreline. Additional considerations with this strategy involve the practicality of changing inlet width. Adjacent infrastructure may make expanding the inlet difficult.

The height of sand waves may also be reduced by increasing the flow velocity. Increasing the flow velocity may change the flow regime from lower to upper, and a plane bed could be stable. To increase the velocity, the inlet cross section would need to be decreased or the tidal prism would need to be increased. Increasing the flow velocity may be hazardous to vessels traveling through the inlet, and decreasing the inlet cross section may require the jetties to be moved.

Alternative dredging methods designed to specifically focus on problem areas, such as sand wave crests, have been tested, but none have proven effective. Granat and Alexander (1991) reviewed “fluidizer dredging” in the Columbia River. During fluidizer dredging, water is jetted into the crest of the sand wave. This procedure decreases the pore pressure and suspends the sediment, which can then be transported to the adjacent trough by the ambient currents. The fluidizer dredge is preferable to conventional dredging because a pipeline is not required, there is no need to find a disposal area, boat traffic is not impeded, and mobilization time is short. However, the fluidizer dredge is difficult to maneuver, and productivity is dependent on the flow conditions. Greater flow velocities can remove more material, but can make it harder to maneuver the dredge. Overall, the fluidizer dredge is less productive, costing more than double conventional dredging (Granat and Alexander 1991). Water injection dredging works best for sand less than 0.2 mm. Such technology would not be applicable at sites with sand waves, because the grain size in these regions is usually coarser.

The final alternative is to stop sediment adjacent to the channel from migrating into the channel. Modifications of the channel design or layout of the channel and/or associated catch basins may prevent sand from migrating into the channel. St. Marys navigation channel is bounded in areas by channel wideners. The wideners are an extension of the navigation channel maintained at the same depth. These areas act as deposition basins which catch the sand before it migrates into the navigation channel.

APPLICATION TO PACKERY CHANNEL: Packery Channel is located 30 km south of Corpus Christi Pass, TX. This natural pass or inlet was open until 1912, when Aransas Pass Inlet at Port Aransas began to be maintained. Since then, the inlet has only been opened intermittently by storms as an overwash pass (Kraus and Heilman 1997). The city of Corpus Christi decided to

reopen and stabilize this inlet to provide permanent access to the Gulf of Mexico from Packery Channel (Figure 16). Construction of the jetties began in September 2003. The inlet was scheduled to be opened in September 2005, but the storm surge from Hurricane Emily breached the inlet on 20 July 2005, and other hurricanes, as well as budget constraints, have hindered construction, which is on-going.

The potential development of bed forms that might impede navigation is a concern for the U.S. Army Corps of Engineers. Grain size data collected by the Shoreline Environmental Research Facility (SERF)[1] and flow velocity measurements made by the Division of Nearshore Research[2], Texas A&M University-Corpus Christi, under contract with the U.S. Army Engineer District, Galveston, can be analyzed to evaluate this possibility. The channel is planned to be 3 m deep (mllw). Current velocity in the undredged channel opened by Hurricane Emily has been recorded as great as 0.95 m/sec, with mean peak velocity of approximately 0.6 m/sec, and grain size closest to the current meter is 0.17 mm. These values suggest that only ripples will develop in this inlet (Figure 17). However, if the velocity in this inlet continues to increase, sand waves may become a problem. Given that this inlet had a tendency to close before it was jettied and dredged, the sand supply is likely sufficient to build sand waves. In evaluating the likelihood that large bed forms will develop in this inlet, the potential development of a lag deposit and the effect of unsteady tidal currents, as well as the strong wind-driven current along the Texas coast, should also be considered.

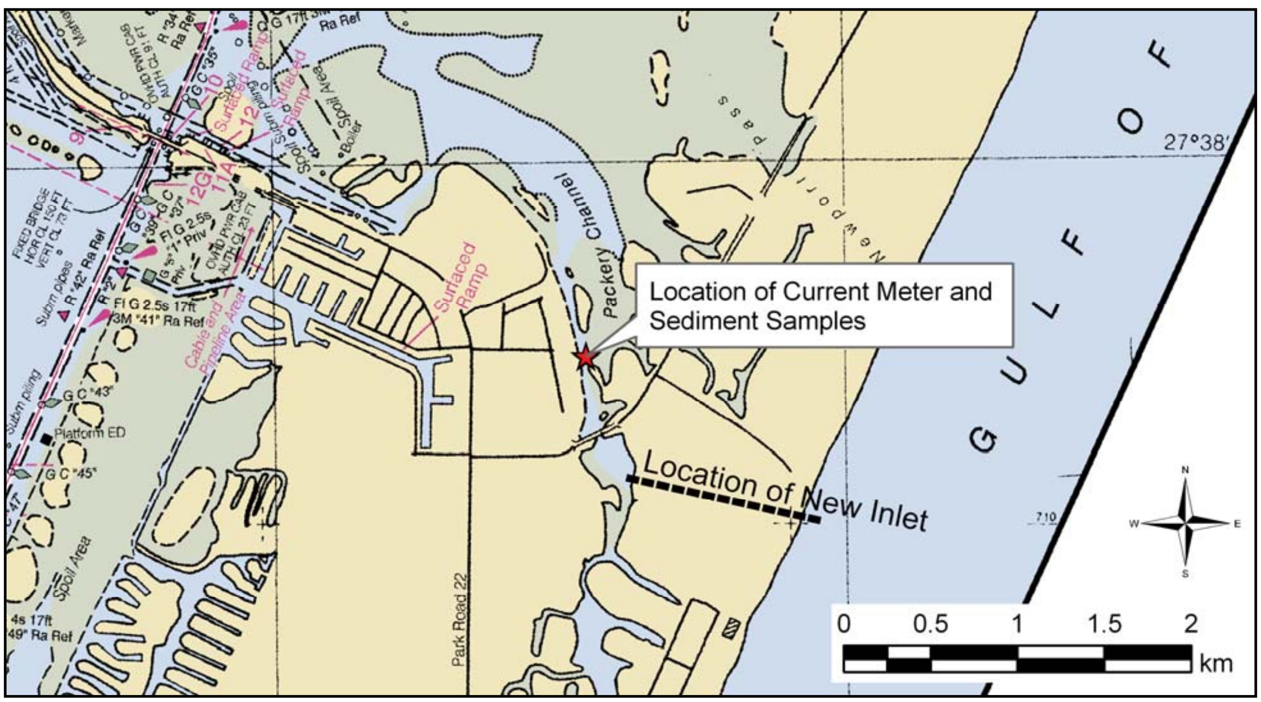

Figure 16. Location map of Packery Inlet, TX. National Oceanic and Atmospheric Administration National Ocean Service Coast Survey Nautical Chart Number 11308.

[1] Shoreline Environmental Research Facility, Texas A&M University Corpus Christi, Texas, http://www.serf.tamus.edu/ResearchProjects/TexasInletsOnline/ PackeryChannel/Packery%20Channel%20Main.htm.

[2] Division of Nearshore Research, Texas A&M University, Corpus Christi, TX, http://lighthouse.tamucc.edu/qc/138.

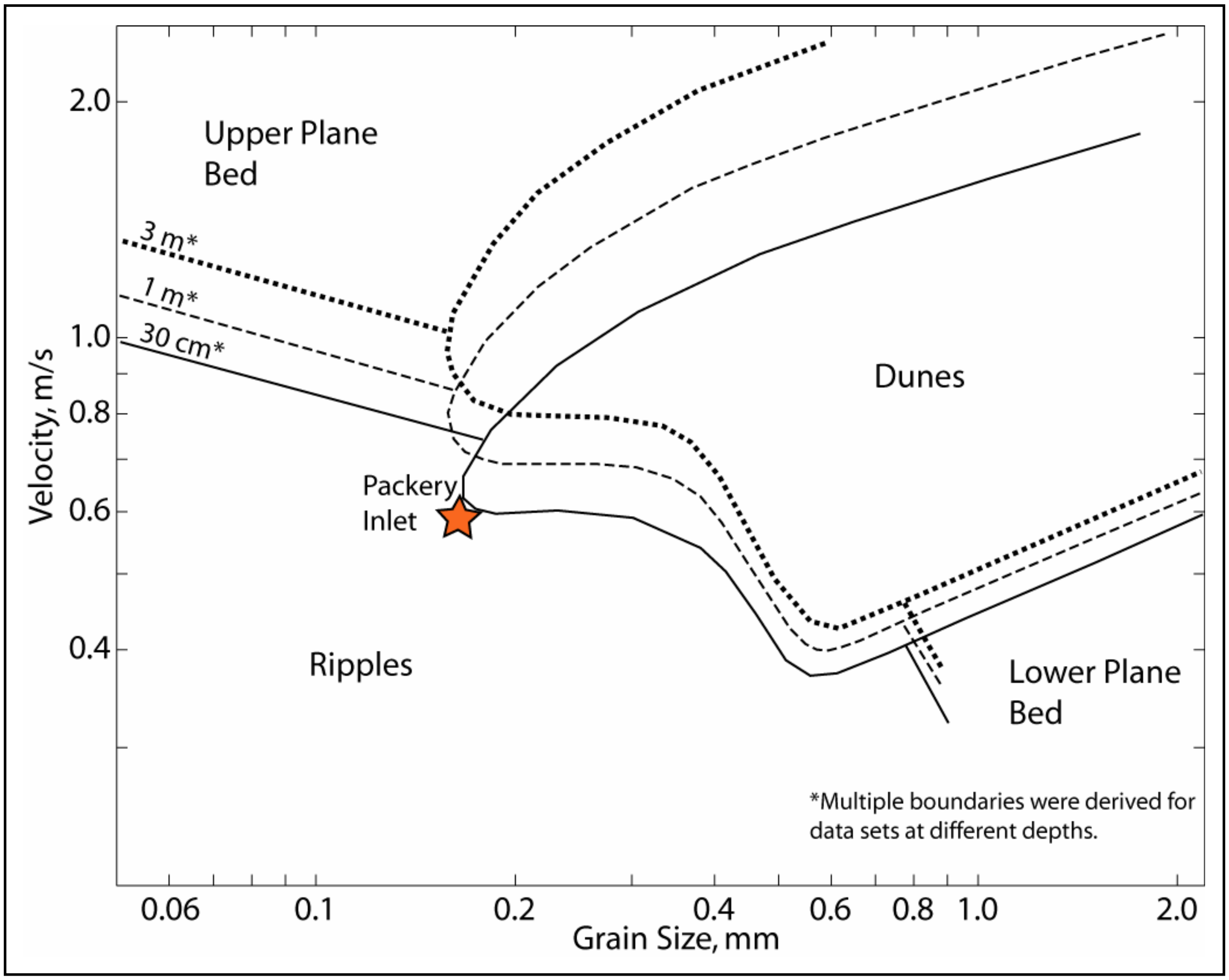

Figure 17. Bed form stability after Southard and Boguchwal (1990) with data from Packery Channel, TX.

CONCLUSIONS: Available studies indicate that water depth, grain size, and flow velocity control the distribution of bed forms in the natural environment. Data presented here for tidal navigation channels show that grain size and flow velocity exert more control over the distribution of bed forms than depth. The conventional idea that bed form-size scales with water depth does not hold true for this field data set. Typically, sand waves develop where the grain size is larger than 0.16 mm and the current speed exceeds 0.6 m/sec. However, these criteria are poor predictors of bed form development, because most inlets meeting them do not exhibit large bed forms. Therefore, factors in addition to grain size and flow velocity must control bed form development. Additional controlling factors include availability of unconsolidated sand-sized material, existence of a lag deposit that inhibits growth of sand waves, and the response time of channel morphology to changes in flow conditions.

Existing formulas predicting bed form wavelength and height are based on water depth. However, most of these formulas are poor predictors because the dimensions of the bed forms are weakly correlated to water depth in deeper water. The literature suggests that this relationship is stronger in shallow water, but most navigation channels are not shallow.

Identified mitigation options are limited. Altering the current speed, grain size, or water depth of a channel are, in general, impractical. Dredging techniques focusing on specific areas such as bed form crests have proven to be inefficient, and traditional channel dredging is preferred (Granat and Alexander 1991). Strategic channel design and location of deposition basins may be the most practical and efficient option.

POINTS OF CONTACT: Ms. Julie Dean Rosati and Dr. Nicholas C. Kraus, of the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, provided motivation and constructive review of this technical note as part of the Coastal Inlets Research Program. The authors also acknowledge the contribution of the U.S. Army Corps of Engineer Districts in the development of the database on sand waves in Federal navigation channels compiled for this CHETN. Without their cooperation, populating the database would have been impossible. Ms. Rosati's assistance in facilitating correspondence between the authors and the Districts is much appreciated.

Questions about this technical note can be addressed to Ms. Shelley Whitmeyer (e-mail: *shelleyj@bu.edu*). For information about the Coastal Inlets Research Program, contact the Program Manager, Dr. Nicholas C. Kraus at *Nicholas.C.Kraus@erdc.usace.army.mil*. This CHETN should be cited as follows:

> Whitmeyer, S. J., and D. FitzGerald. 2006. *Sand waves that impede navigation of inlet navigation channels.* ERDC/CHL CHETN IV-68, Vicksburg, MS: U.S. Army Engineer Research and Development Center.
> *http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=ARTICLES;370*

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